Preprint
UCRL-JC-141556

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C. W. Mauche, J. A. Mattei, F. M. Bateson

This article was submitted to Evolution of Binary and Multiple Star Systems, Bormio, Italy, June 25-July 1, 2000

U.S. Department of Energy

Lawrence Livermore National Laboratory

November 15, 2000

This work was performed under the auspices of the United States Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Evolution of Binary and Multiple Star Systems
ASP Conference Series, Vol. ?, 2001
P. Podsiadlowski & S. Rappaport

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Christopher W. Mauche

Lawrence Livermore National Laboratory, L-43, 7000 East Avenue, Livermore, CA 94550

Janet A. Mattei

American Association of Variable Star Observers, 25 Birch Street, Cambridge, MA 01238

Frank M. Bateson

Variable Star Section/Royal Astronomical Society of New Zealand, P.O. Box 3093, Greerton, Tauranga, New Zealand

Abstract. We combine AAVSO and VSS/RASNZ optical and *Extreme Ultraviolet Explorer* EUV light curves of dwarf novae in outburst to place constraints on the nature of dwarf nova outbursts. From the observed optical–EUV time delays of ≈ 0.75–1.5 days, we show that the propagation velocity of the dwarf nova instability heating wave is ≈ 3 km s^{-1}.

1. Introduction

Dwarf nova outbursts are understood to be the result of an instability in the rate of mass transfer through the accretion disk surrounding the white dwarf in these semidetached binaries. The instability can be triggered at large or small disk radii, resulting in normal, fast-rise outbursts or anomalous, slow-rise outbursts, respectively. In either case, the beginning of the outburst is signaled by a rise of the optical flux, followed by a rise of the UV flux as material sinks through the disk, converting gravitational potential energy into rotational kinetic energy and radiation. This is followed by a rise in the EUV flux as material passes through the boundary layer between the disk and the surface of the white dwarf, where it converts its prodigious rotational kinetic energy into radiation.

Because the optical and EUV flux of dwarf novae is produced in physically distinct regions of the accretion disk, light curves in these wavebands provide important diagnostics of the nature of dwarf nova outbursts. Toward this end, we present optical and EUV light curves of dwarf novae observed by the *Extreme Ultraviolet Explorer* (*EUVE*) satellite.

2. EUVE Observations

During the past seven years, *EUVE* was used to observe four dwarf novae in outburst: SS Cyg in narrow and wide, normal and anomalous outbursts; U Gem in normal outburst (twice); VW Hyi in normal and superoutburst (twice); and OY Car in superoutburst (twice). These eleven observations were originally obtained for varying reasons, and on a couple of occasions they were coordinated with other satellites (*RXTE*, *Voyager*, *HST*) sensitive in other wavebands (hard X-rays, FUV, UV). Details of the *EUVE* observations are provided in Table 1. Note that the exposures are 55–274 ks, and because the satellite takes data for $\lesssim$ one third of its orbit, the EUV light curves span intervals of 2–13 days.

Table 1. Journal of *EUVE* Observations

Star	Date (M/Y)	Interval (JD−2400000)	Exp. (ks)	Type of Outburst	Comment
SS Cyg	08/93	49216.58–222.86	179.4	Anom. Wide	
U Gem	12/93	49350.00–361.15	249.0	Normal	
VW Hyi	06/94	49505.46–507.66	89.4	Super	
SS Cyg	06/94	49526.67–536.69	147.8	Normal Wide	
VW Hyi	07/95	49906.70–917.29	183.8	Normal	+ *Voyager*
VW Hyi	05/96	50210.58–218.47	55.4	Super	+ *RXTE*
SS Cyg	10/96	50366.40–379.45	208.1	Normal Narrow	+ *RXTE*
OY Car	03/97	50534.46–537.64	94.8	Super	
U Gem	11/97	50760.27–766.85	150.0	Normal	+ *RXTE*
SS Cyg	06/99	51336.84–349.67	274.0	Anom. Narrow	+ *RXTE*
OY Car	02/00	51597.66–601.26	69.1	Super	&*HST*
Net Exposure:		87.4 days	1.7 Ms		

3. Optical and EUV Light Curves

Optical light curves of these outbursts were constructed from visual magnitude estimates and CCD photometric measurements obtained by members of the American Association of Variable Star Observers (AAVSO) and the Variable Star Section/Royal Astronomical Society of New Zealand (VSS/RASNZ). EUV light curves were constructed from the *EUVE* deep survey photometer (DS) or short wavelength spectrometer (SW) in those instances when the DS was turned off (during the peak of the 10/96 outburst of SS Cyg, both outbursts of U Gem, and the 6/94 outburst of VW Hyi). The resulting optical and EUV light curves are shown in Figures 1–6, with the *EUVE* DS and SW data shown by filled circles and squares, respectively, and the optical data shown by dots and open diamonds (measurements) or carets (upper limits). Half-day averages of the optical measurements are shown by the histograms for SS Cyg and U Gem. In Figure 4 the *Voyager* 950–1150 Å (FUV) flux density light curve of VW Hyi in normal outburst is shown by the filled triangles.

4. Discussion

The anomalous outbursts of SS Cyg (Fig. 1) manifest the gradual increase of the optical and EUV light curves expected for inside-out outbursts. The optical and EUV flux rises during the beginning of these outbursts as the heating wave sweeps outward through the disk, causing more and more material to flow

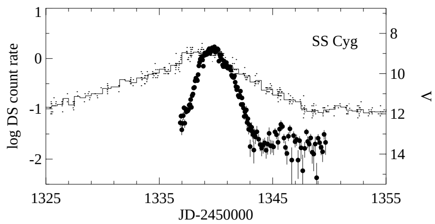

Figure 1. Anomalous (slow-rise) outbursts of SS Cyg.

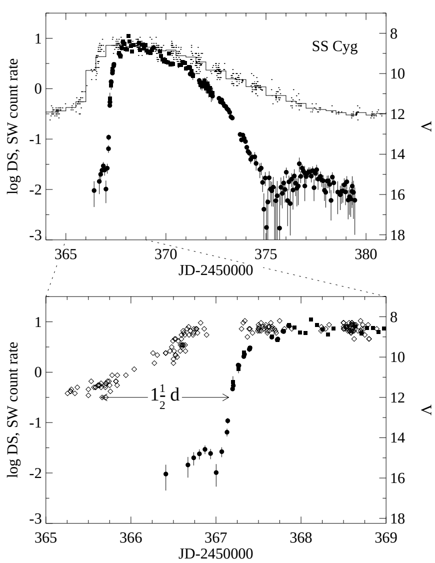

Figure 2. Normal (fast-rise) outbursts of SS Cyg. The optical-EUV delay is ≈ 1.5 days.

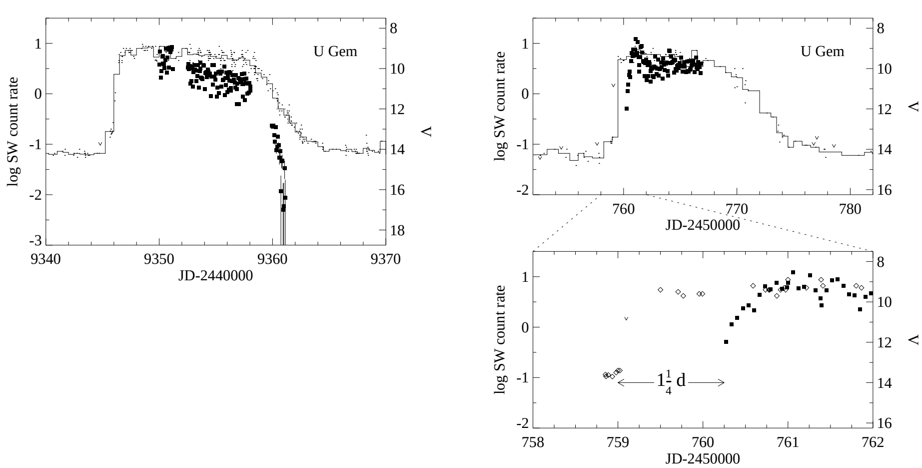

Figure 3. Outbursts of U Gem. The optical-EUV delay is ≈ 1.25 days.

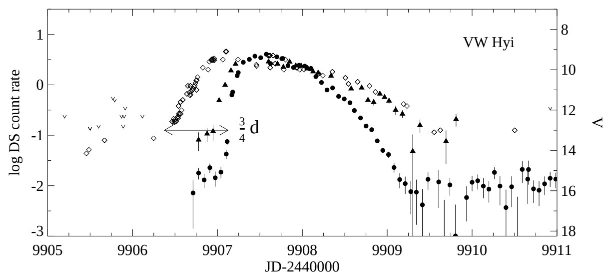

Figure 4. Normal outburst of VW Hyi. The optical-FUV delay is ≈ 0.5 days and the optical-EUV delay is ≈ 0.75 days.

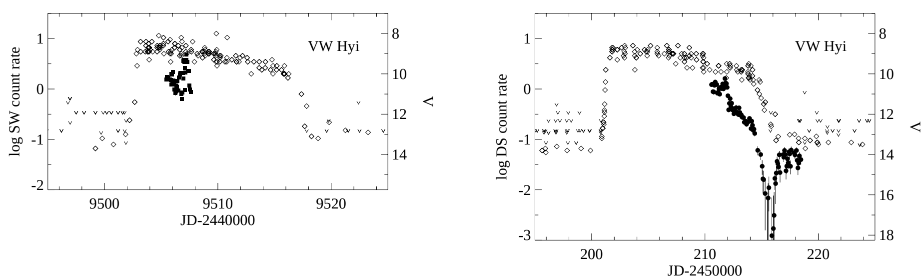

Figure 5. Superoutbursts of VW Hyi.

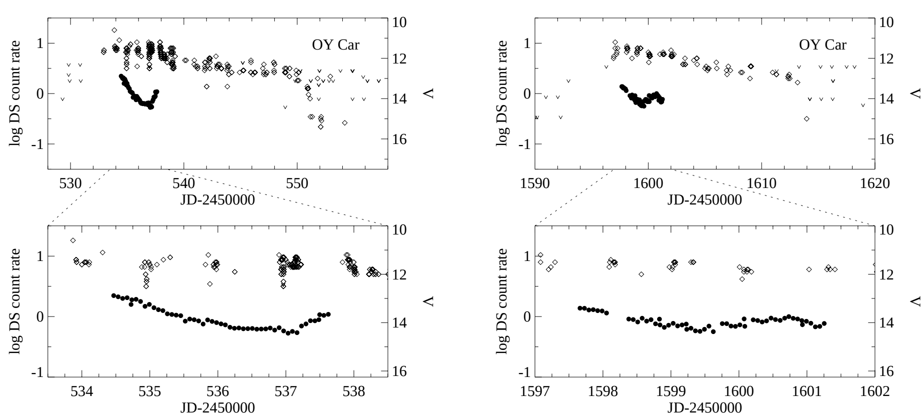

Figure 6. Superoutbursts of OY Car.

through the disk and boundary layer onto the white dwarf. In contrast, the normal outbursts of SS Cyg (Fig. 2), U Gem (Fig. 3), and VW Hyi (Fig. 4) manifest the fast increase of, and the delay between, the optical and EUV light curves expected for outside-in outbursts. As measured from the initial rise of the optical light curves, the delay of the rise of the EUV light curves is ≈ 1.5, 1.25, and 0.75 days for SS Cyg, U Gem, and VW Hyi, respectively. In VW Hyi, the FUV light curve rises ≈ 0.5 days after the optical light curve and ≈ 0.25 days before the EUV light curve, but falls as slowly as the optical light curve, consistent with the expectation that the accretion disk and not the boundary layer is the source of the FUV flux. We were not able to observe the rise of the EUV light curves of the superoutbursts of VW Hyi (Fig. 5) or OY Car (Fig. 6), but during both observations of OY Car the EUV light curve was observed to fall and then rise while the optical light curve was declining only slowly. This behavior is evidence for a decrease and subsequent increase of the mass-accretion rate onto the white dwarf, as might be expected if a normal outburst is rejuvenated by an increase in the mass-accretion rate driven by the tidal instability expected for such high mass-ratio binaries.

The observed optical-EUV delays of the normal outbursts of SS Cyg, U Gem, and VW Hyi provide the most direct measurement of the velocity of the heating wave which transforms the disk from quiescence to outburst. Assuming the system parameters shown in Table 2, that the radius of the disk is $R_{\rm disk} \approx 0.7 \times R_{\rm L1}$, and that the disk instability starts at the outer edge of the disk, the velocity of the heating wave $v \approx R_{\rm disk}/{\rm delay} \approx 3$ km s^{-1}. This result is consistent with $v = \alpha c_{\rm s}$ if the viscosity parameter $\alpha \approx 0.2$ and the sound speed $c_{\rm s} = 10\,(T/10^4~{\rm K})^{1/2} \approx 15$ km s^{-1}.

Table 2. System Parameters[a] and Velocity of the Heating Wave

Parameter	SS Cyg	U Gem	VW Hyi
$P_{\rm orb}$ (days)	0.2751	0.1769	0.0743
M_1 ($M_\odot$)	1.19	1.26	0.63
M_2 ($M_\odot$)	0.70	0.57	0.11
$q = M_1/M_2$	1.69	2.17	6
$R_{\rm L1}/a$	0.43	0.45	0.54
$a = [(P_{\rm orb}/2\pi)2G(M_1+M_2)]^{1/3}$ (cm)	1.5×10^{11}	1.1×10^{11}	4.7×10^{10}
$R_{\rm disk} \approx 0.7 \times R_{\rm L1}$ (cm)	4.6×10^{10}	3.5×10^{10}	1.8×10^{10}
delay (days)	1.5	1.25	0.75
$v \approx R_{\rm disk}/{\rm delay}$ (km s^{-1})	3.5	3.3	2.7

[a]Ritter, H., & Kolb, U. 1998, A&A, 129, 83

Acknowledgments. We thank the many members of the AAVSO and VSS/RASNZ for providing the triggers for our satellite observations and for the data used to construct the optical light curves. We are grateful to J. Cannizzo for years of discussions about the dwarf nova instability theory and to J. Holberg and J. Collins for acquiring and reducing the *Voyager* data shown in Fig. 4. J.A.M. acknowledges NASA grants NAG5-3144, -0727, -7357, -7358, and 06545.03A. C. W. M.'s contribution to this work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.